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(54) **ELECTRODESULFURIZATION OF HEAVY OILS**

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C10G 45/00 (2006.01)

(52) **U.S. Cl.** **208/209**; 204/168

(58) **Field of Classification Search** .... 208/208 R, 208/209, 210, 211, 212; 204/168
See application file for complete search history.

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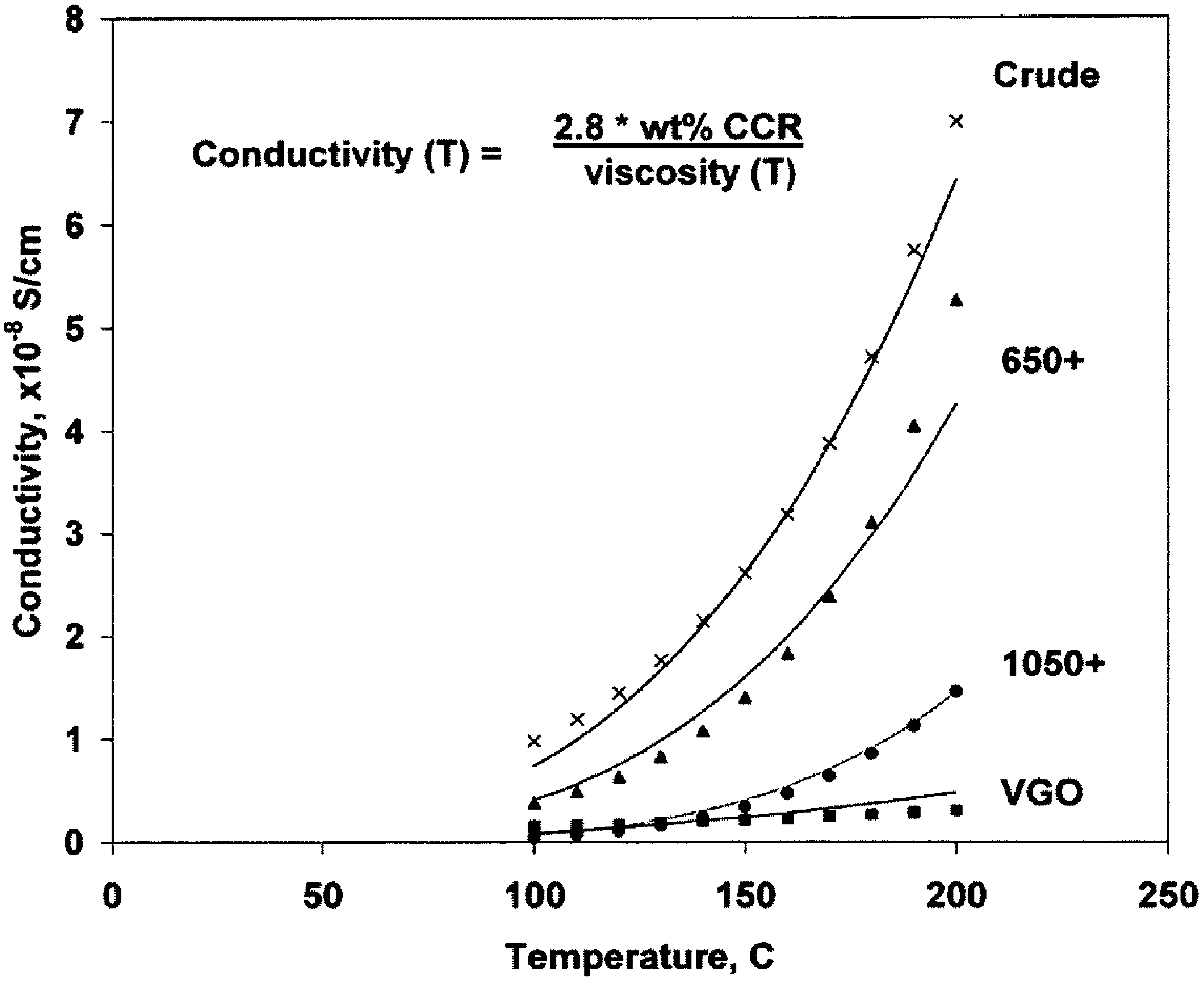
(57) **ABSTRACT**

The electrodesulfurization of heavy oils wherein a feedstream comprised of bitumen or heavy oil is conducted, along with an effective amount of hydrogen, to an electrochemical cell. A current is applied to the cell wherein sulfur from the feedstream combines with hydrogen to form hydrogen sulfide which is removed.

15 Claims, 3 Drawing Sheets

Figure 1



Conductivity (T) = $\frac{2.8 * \text{wt\% CCR}}{\text{viscosity (T)}}$
Crude
650+
1050+
VGO
Conductivity, x10^{-8} S/cm
0
1
2
3
4
5
6
7
8
Temperature, C
0
50
100
150
200
250

Figure 2

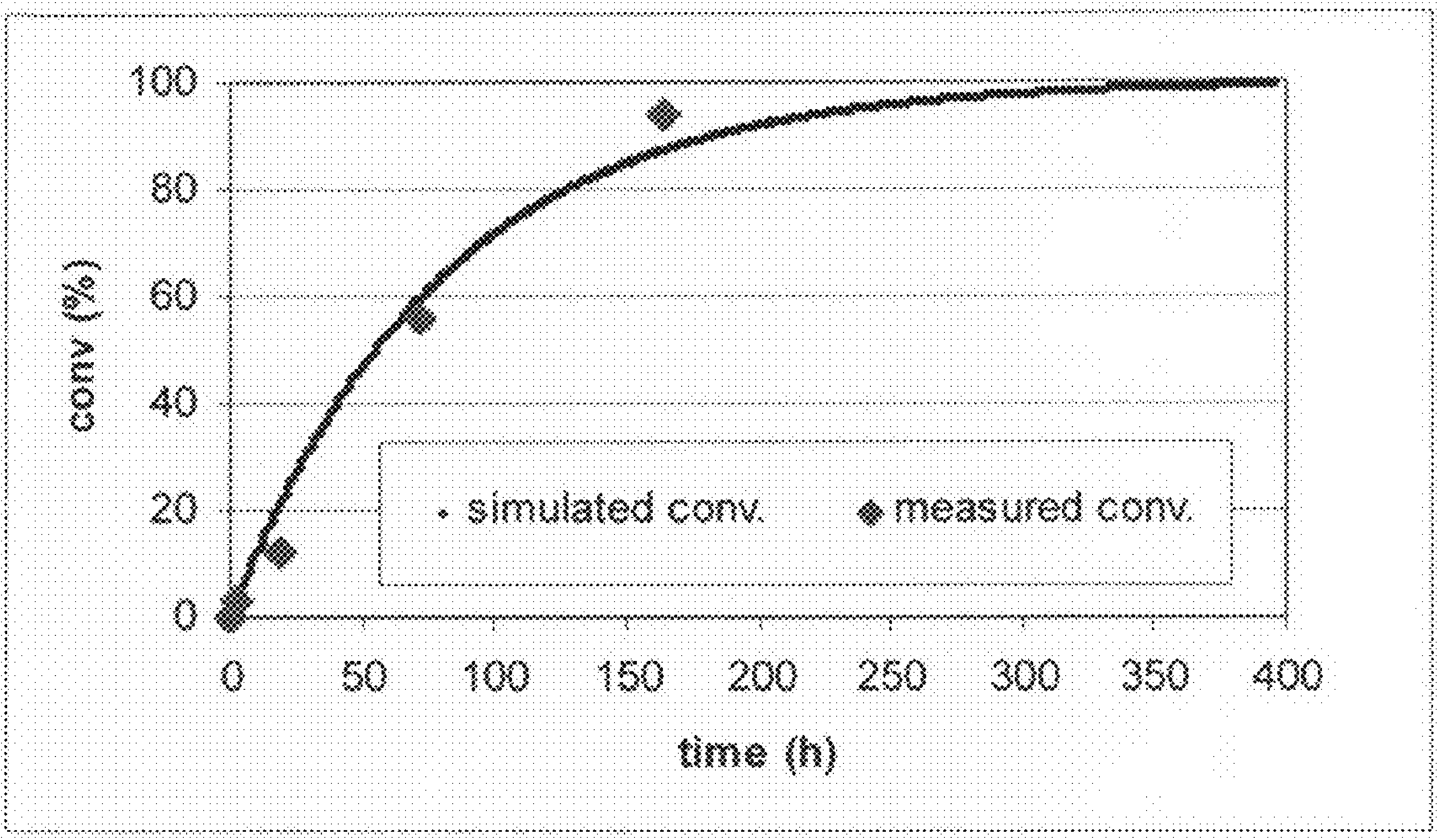
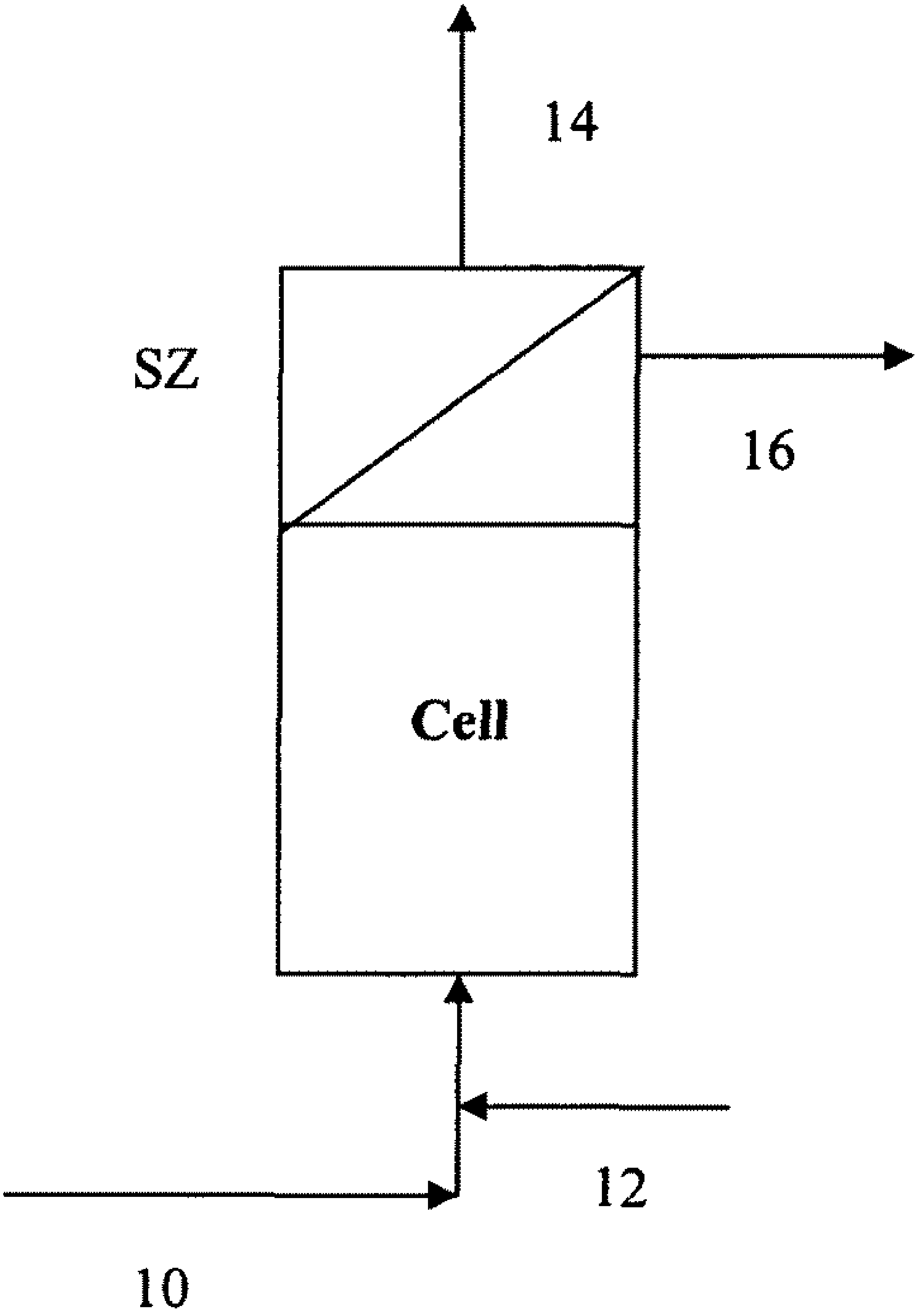

100
80
60
40
20
0
conv (%)
0
50
100
150
200
250
300
350
400
time (h)
• simulated conv.
◆ measured conv.

Figure 3



ELECTRODESULFURIZATION OF HEAVY OILS

This Application claims the benefit of U.S. Provisional Application No. 61/008,415 filed Dec. 20, 2007.

FIELD OF THE INVENTION

This invention relates to the electrodesulfurization of heavy oils wherein a feedstream comprised of a heavy oil is conducted, along with an effective amount of hydrogen, to an electrochemical cell. A current is applied to the cell wherein sulfur from the feedstream combines with hydrogen to form hydrogen sulfide which is removed.

BACKGROUND OF THE INVENTION

Bitumen, in this case, refers to the naturally occurring heavy oil deposits such as the Canadian bitumens found in Cold Lake and Athabasca. Bitumen is a complex mixture of chemicals and typically contains hydrocarbons, heteroatoms, metals and carbon chains in excess of 2,000 carbon atoms. A variety of technologies are used to upgrade heavy oil feedstreams including bitumens. Such technologies include thermal conversion, or coking, that involves using heat to break the long heavy hydrocarbon molecular chains in these high molecular weight hydrocarbon feedstreams. Thermal conversion includes such processes as delayed coking and fluid coking. Delayed coking is a process wherein a heavy oil feedstream is heated to about 932° F. (500° C.), then pumped into one side of a double-sided coker where it cracks into various products ranging from solid coke to vapor products. Fluid coking is similar to delayed coking except it is a continuous process. In a fluid coking process, a heavy oil feedstream is heated to about 932° F. (500° C.), but instead of pumping the heavy oil feedstream to a coker it is sprayed in a fine mist around the entire height and circumference of the coker. The heavy oil feedstream cracks into a vapor and the resulting coke is in the form of a powder-like form, which can be drained from the bottom of the coker.

Another technology used to upgrade heavy oil feedstreams is catalytic conversion which is used to crack larger molecules into smaller, refineable hydrocarbons in the presence of a cracking catalyst. High-pressure hydrogen is often used in catalytic conversion. While catalytic conversion is more expensive than thermal conversion, it produces a higher yield of upgraded product.

Distillation is also used for upgrading heavy oil feedstream, including bitumens, wherein the heavy oil feedstream components are separated in a distillation tower into a variety of products that boil at different temperatures, The lightest hydrocarbons with the lowest boiling points travel as a vapor to the top of the tower, heavier and denser hydrocarbons with higher boiling points collects as liquids lower in the tower.

While the above mentioned technologies are useful for converting a portion of heavy oils including bitumens to lighter and more valuable products, such technologies are not particularly useful for reducing the sulfur content of such feedstocks. One important technology that has been used to reduce the sulfur content (as well as nitrogen and trace metal content) from such feedstocks is hydrotreating. In hydrotreating, or hydrodesulfurization, the heavy oil feedstream is contacted with hydrogen and a suitable desulfurization catalyst at elevated pressures and temperatures. The process typically requires the use of hydrogen pressures ranging preferably from about 700 to about 2,500 psig and temperatures ranging from about 650° F. (343° C.) to about 800° F. (426° C.), depending on the nature of the feedstock to be desulfurized and the amount of sulfur required to be removed.

Hydrotreating is efficient in the case of distillate oil feedstocks but less efficient when used with heavier feedstocks such as bitumens and residua. This is due to several factors. First, most of the sulfur in such feedstocks is contained in high molecular weight molecules, and it is difficult for them to diffuse through the catalyst pores to the catalyst surface. Furthermore, once at the surface, it is difficult for the sulfur atoms contained in these high molecular weight molecules to sufficiently contact the catalyst surface. Additionally, such feedstocks may contain large amounts of asphaltenes that tend to form coke deposits on the catalyst surface under the process conditions, thereby leading to the deactivation of the catalyst. Moreover, high boiling organometallic compounds present in such heavy oil feedstocks decompose and deposit metals on the catalyst surface thereby diminishing the catalyst life time. Severe operating conditions cause appreciable cracking of high boiling oils thereby producing olefinic fragments which, themselves, consume hydrogen, thereby lowering the process efficiency and increasing costs.

Alternate desulfurization processes that have been employed in the past used alkali metal dispersions, such as sodium, as desulfurization agents. One such process involves contacting a hydrocarbon fraction with a sodium dispersion. The sodium reacts with the sulfur in the feedstream to form dispersed sodium sulfide (Na_2S). However, is not commercially attractive, particularly for treatment of high boiling, high sulfur content, heavy oil feedstreams due to: (a) the high cost of sodium, (b) problems related to removal of sodium sulfide formed in the process, (c) the impracticability of regenerating sodium from the sodium sulfide, (d) the relatively low desulfurization efficiency due, in part, to the formation, of substantial amounts of organo sodium salts, (e) a tendency to form increased concentrations of high molecular weight polymeric components (asphaltenes), and (f) the failure to adequately remove metal contaminants (iron, nickel, vanadium) from the feed as is observed in the competitive catalytic hydrodesulfurization process.

While various attempts have been made to mitigate some of the above-mentioned problems, low desulfurization efficiency has still remained an unsolved problem. It has been speculated that the low efficiency is due in part to the formation of organo-sodium compounds formed either by reaction of the sodium with acidic hydrocarbons, addition of sodium to certain reactive olefins or as products obtained when sodium cleaves certain of the organic ethers, sulfides and amines contained in the oil. Formation of these organo-sodium compounds, which are desulfurization inactive materials, effectively removes a portion of the sodium that otherwise would be available for the desulfurization reaction. Sodium in excess of the theoretical amount for desulfurization must therefore be added to compensate for organo-sodium compound formation. Moreover, a hydrocarbon insoluble sludge which forms in the course of the sodium-treating reaction (apparently comprised primarily of organo-sodium compounds), makes the reaction mixture extremely viscous and hence impairs mixing and heat transfer performance in the reactor.

Some work has been done to develop electrochemical processes to desulfurize crudes and heavy oils, such as bitumen. Electrochemical processes, such as that taught in U.S. Pat. No. 6,877,556 require the use of reagents such as solvents, electrolytes, or both. Use of such expensive reagents adds to the complexity of those processes since their recovery from the bitumen is required for economic reasons and thus, such processes are not commercially attractive.

Therefore, there remains a need in the art for improved process technology-capable of effectively and economically removing sulfur from heavy petroleum feedstreams.

SUMMARY OF THE INVENTION

In accordance with a preferred embodiment of the present invention there is provided a process for removing sulfur from heavy oil feedstreams containing sulfur-containing molecules, which process comprises:

a) heating and pressurizing said heavy oil feedstream to a temperature of about 400° F. (204° C.) to about 800° F. (426° C.) and a pressure of about 200 psig to about 700 psig;

b) passing said heated and pressurized heavy oil feedstream and an effective amount of hydrogen to an electrochemical cell and subjecting the heavy oil feedstream to a voltage in the range of about 4V to about 500V and a current density of about 10 mA/cm^2 to about 1000 mA/cm^2, thereby reducing at least a portion of the sulfur-containing molecules to hydrogen sulfide and resulting in a product stream comprised sulfur-lean heavy oil product stream and hydrogen sulfide;

c) separating said hydrogen sulfide from said sulfur-lean heavy oil product stream in a gas/liquid separation zone; and

d) recovering the sulfur-lean heavy oil product stream.

In another preferred embodiment, the electrochemical cell is a divided cell.

In another preferred embodiment, the heavy oil feedstream is a bitumen.

In still another preferred embodiment, at least a portion of the hydrogen sulfide stream produced is send to a Claus plant wherein sulfur is recovered as elemental sulfur.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** hereof is a plot of conductivity versus temperature for various distillation cuts of a petroleum crude.

FIG. **2** hereof is a plot conversion of dibenzothiophene versus time for Example 3 hereof. This figure shows the overall degree of desulfurization appears to follow first order kinetics.

FIG. **3** hereof is a simplified flow scheme of one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The process of the present invention is preferably practiced on sulfur-containing heavy oil feedstreams. In a preferred embodiment of the present invention, the heavy oil feedstream contains at least about 10 wt. % of material boiling in excess of about 1050° F. (565° C.) at atmospheric pressure (defined as 0 psig), more preferably at least about 25 wt. % of material boiling above about 1050° F. (565° C.) at atmospheric pressure. Unless otherwise noted, all boiling temperatures herein are designated at atmospheric pressure (defined as 0 psig). Non-limiting examples of such feedstreams include whole, topped or froth-treated bitumens, heavy oils, whole or topped crude oils and residua. These include crude oils obtained from any area of the world, as well as heavy gas oils, shale oils, tar sands or syncrude derived from tar sands, coal oils, and asphaltenes. Additionally, both atmospheric residuum, boiling above about 650° F. (343° C.) and vacuum residuum, boiling above about 1050° F. (565° C.) can be treated in accordance with the present invention. The preferred feedstream to be treated in accordance with the present invention is bitumen. Bitumen is generally defined as a mixture of organic liquids that are highly viscous, black, sticky, and composed primarily of highly condensed polycyclic aromatic hydrocarbons. Bitumen is obtained from extraction from oil shales and tar sands. Such heavy feedstreams contain an appreciable amount of so-called "hard" sulfur, such as dibenzothiophenes (DBTs), that are very difficult to remove by conventional means.

These heavy feedstreams are sometimes desulfurized with use of sodium, as previously mentioned. In the sodium upgrading of heavy oil feedstreams, including bitumens, elemental sodium acts as a chemical reductant, each sodium atom transferring a single electron to molecules in the heavy oil feedstream thereby initiating free radical desulfurization chemistry. In the process of the present invention, reduction, or the generation of free radicals by transfer of electrons, is accomplished by use of an electrode polarized to the reducing potential of the target sulfur-containing molecules. The primary advantage of this invention is that the sulfur is released from the heavy oil as hydrogen sulfide, in contrast to being released as sodium sulfide when sodium is used. Regeneration of elemental sodium from sodium sulfide is currently the critical technological limitation for the sodium process. The hydrogen sulfide produced by the practice of the present invention can be converted to sulfur in a Claus plant. Further, the resulting sulfur-lean heavy oil product stream, or bitumen, is similar to that produced by the sodium process. The number of electrons required to initiate the radical chemistry in the process of the present invention will be roughly equivalent to the number required to regenerate sodium in the sodium treating process.

The process of the present invention does not require the addition of an electrolyte to the heavy oil feedstream, but rather, relies on the intrinsic conductivity of the heavy oil feedstream at elevated temperatures. It will be understood that the term "heavy oil" as used herein includes both bitumen and heavy oil petroleum feedstreams, such as crude oils, atmospheric resids, and vacuum resids. This process is preferably utilized to upgrade bitumens and/or crude oils that have an API gravity less than about 15. The inventors hereof have undertaken studies to determine the electrochemical conductivity of crudes and residues (which includes bitumen and heavy oils) at temperatures up to about 572° F. (300° C.) and have demonstrated an exponential increase in electrical conductivity with temperature as illustrated in FIG. **1** hereof. It is believed that the electrical conductivity in crudes and residues is primarily carried by electron-hopping in the π-orbitals of aromatic and heterocyclic molecules. Experimental support for this is illustrated by the simple equation, shown in FIG. **1** hereof, that can be used to calculate the conductivity of various cuts of a crude using only its temperature dependent viscosity and its Conradson carbon (Concarbon) content. The molecules that contribute to Concarbon are primarily the large multi-ring aromatic and heterocyclic components.

A 4 mA/cm^2 electrical current density at 662° F. (350° C.) with an applied voltage of 150 volts and a cathode-to-anode gap of 1 mm was measured for an American crude oil. Though this is lower than would be utilized in preferred commercial embodiments of the present invention, the linear velocity for this measurement was lower than the preferred velocity ranges by about three orders of magnitude: 0.1 cm/s vs. 100 cm/s. Using a 0.8 exponent for the impact of increased flow velocity on current density at an electrode, it is estimated that the current density would increase to about 159 mA/cm^2 at a linear velocity of about 100 cm/s. This suggests that more commercially attractive current densities achieved at higher applied voltages. Narrower gap electrode designs or fluidized bed electrode systems could also be used to lower the required applied voltage.

The heavy oil can be that derived from the fractional distillation of crude oil or it can be comprised of bitumen derived from oil sands. Oil sands are typically processed in two main stages to obtain bitumen. The most common extraction process is hot water bitumen extraction where bitumen is produced in a froth consisting of bitumen, water, and inorganic solids. The froth is then treated in a second stage to separate the bitumen. Conventional froth treatment methods include dilution with naphtha followed separation by use of a centrifuge or inclined plane settler, and dilution with heptane followed by gravity settling. Based on this background, the following electrodesulfurization process embodiment for heavy oils, including bitumens, as illustrated in FIG. **3** is proposed.

In FIG. **3**, a heavy oil feedstream is heated to a temperature of about 300° F. to about 800° F., preferably from about 350° F. (176° C.) to about 500° F. (260° C.) and pressurized to a pressure from about 200 psig to about 700 psig, preferably from about 300 psig to about 500 psig and introduced, via line **10**, into a desulfurization electrochemical cell [Cell]. Although the cell may be divided or undivided, undivided cells are preferred. Such systems include stirred batch or flow through reactors. The foregoing may be purchased commercially or made using technology known in the art. Suitable electrodes known in the art may be used. Included as suitable electrodes are three-dimensional electrodes, such as carbon or metallic foams. The optimal electrode design would depend upon normal electrochemical engineering considerations and could include divided and undivided plate and frame cells, bipolar stacks, fluidized bed electrodes and porous three dimensional electrode designs; see *Electrode Processes and Electrochemical Engineering* by Fumio Hine (Plenum Press, New York 1985). While direct current is typically used, electrode performance may be enhanced using alternating current or other voltage/current waveforms.

An effective amount of hydrogen is mixed with feed via line **12**. By "effective amount" we mean at least that amount needed to reduce the sulfur content by at least about 90%, preferably by at least about 95%. Total pressure will be about 10 to about 2000 psig, preferably from about 50 to about 1000 psig, more preferably from about 200 to about 500 psig. This electrochemical cell is preferably comprised of parallel thin steel sheets mounted vertically within a standard pressure vessel shell. The gap between electrode surfaces will preferably be about 1 to about 50 mm, more preferably from about 1 to about 25 mm, and the linear velocity will be in the range of about 1 to about 500 cm/s, more preferably in the range of about 50 to about 200 cm/s. Electrical contacts are only made to the outer sheets. Electrical contacts are only made to the outer sheets. The electrode stack can be polarized with about 4 to about 500 volts, preferably from about 100 to about 200 volts, resulting in a current density of about 10 mA/cm^2 to about 1000 mA/cm^2, preferably from about 100 mA/cm^2 to about 500 mA/cm^2. It will be noted that other commercial cell designs, such as a fluidized bed electrode can also be used in the practice of the present invention. As the heavy oil feedstream passes through the electrochemical cell, the sulfur-bearing molecules will be reduced, and the sulfur will be released as hydrogen sulfide.

The resulting sulfur-lean heavy oil product stream and hydrogen sulfide is sent to a liquid/gas separation zone (SZ) wherein the hydrogen sulfide is separated from the sulfur-lean heavy oil product stream. Any suitable liquid/gas separation technology can be used in the liquid/gas separation zone of

the present invention. Non-limiting examples of liquid/gas separation technologies that can be used in the practice of the present invention include gravity separators, centrifugal separators, mist eliminators, filter van separators and liquid/gas coalescers. The hydrogen sulfide stream is removed from separation zone (SZ) via line **14** and can be recovered or sent to a Claus plant (not shown) for recovery of sulfur and hydrogen. The Claus process is well known in the art and is a significant gas desulfurizing processes for recovering elemental sulfur from gaseous hydrogen sulfide. Typically gaseous streams containing at least about 25% hydrogen sulfide are suitable for a Claus plant. The Claus process is a two step process, thermal and catalytic. In the thermal step, hydrogen sulfide-laden gas reacts in a substoichiometric combustion at temperatures above about 1562° F. (850° C.) such that elemental sulfur precipitates in a downstream process gas cooler. The Claus reaction continues in a catalytic step with activated alumina or titanium dioxide, and serves to boost the sulfur yield.

The sulfur-lean heavy oil product stream, which will be substantially reduced in sulfur, is recovered via line **16**. Significant heating of the heavy oil will occur as it passes through the cell due to resistive heating and thus, in an embodiment, the sulfur-lean heavy oil product stream produced by the current process can be sent to a heat exchange zone wherein it can be used to heat the incoming feed.

Proposed Electrodesulfurization Pathway

A model compound, dibenzothiophene (DBT), is used to illustrate the principle of the following examples. A combination of electrochemical and thermal reactions achieves substantially complete desulfurization, as exemplified as follows.

$$\mathrm{DBT}+2e^{-}+\mathrm{H2}\rightarrow \mathrm{biphenyl}+\mathrm{H_2S} \qquad [1]$$

Charge neutrality is ensured by the anode, which will be removing electrons from the feedstream. The proposed electrochemical desulfurization process is demonstrated by the following examples.

For the following examples, a 300-cc autoclave (Parr Instruments, Moline, Ill.) was modified to allow two insulating glands (Conax, Buffalo, N.Y.) to feed through the autoclave head. Two cylindrical stainless steel (316) mesh electrodes were connected to the Conax glands, where a power supply (GW Laboratory DC Power Supply, Model GPR-1810HD) was connected to the other end. The autoclave body was fitted with a glass insert, a thermal-couple and a stirring rod. The autoclave was charged with the desired gas under pressure and run either in a batch or a flow-through mode.

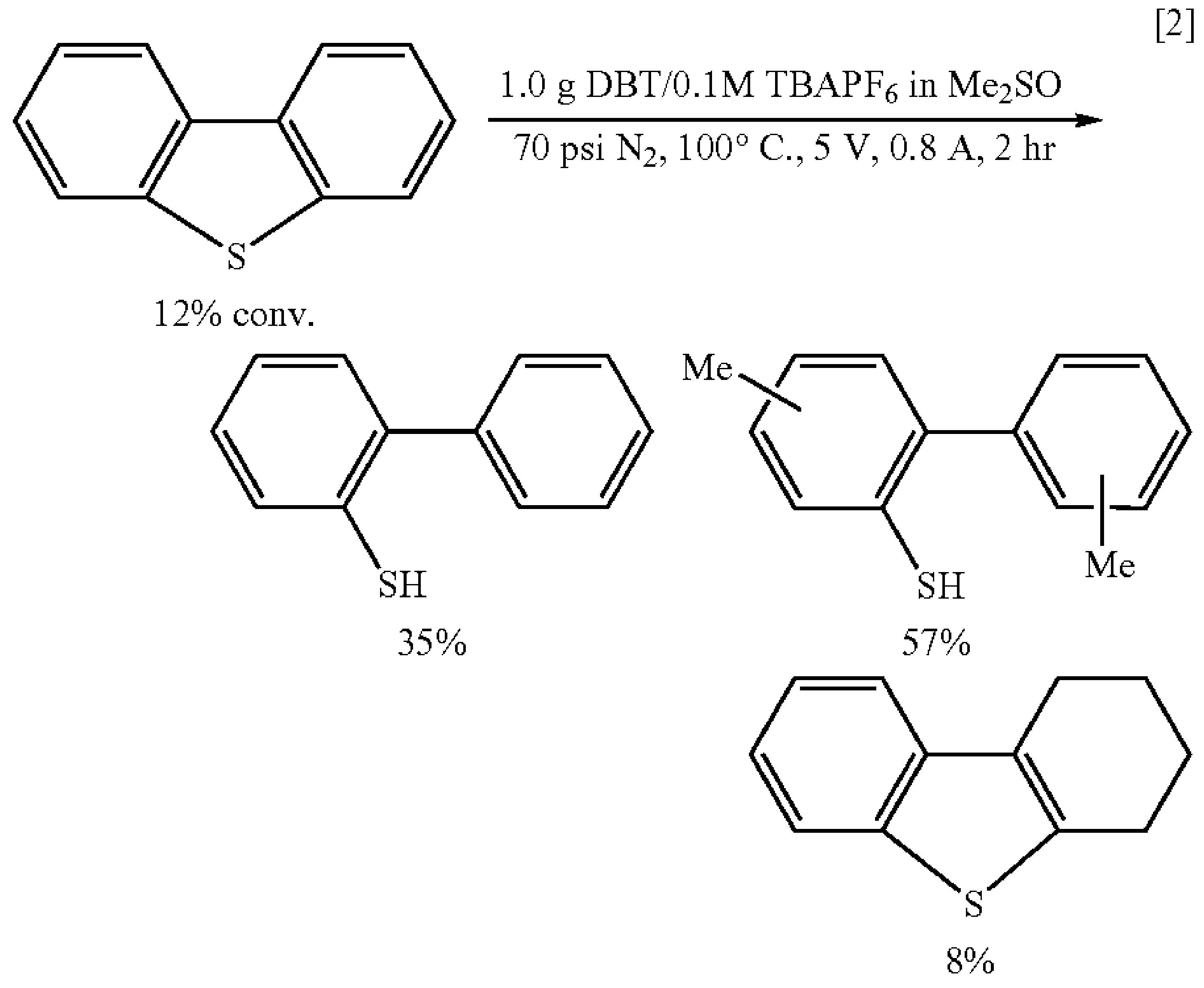
Comparative Example

Electrochemical Treatment of DBT Under N_2 in Dimethyl Sulfoxide Solvent with Tetrabutylammonium Hexafluorophosphate Electrolyte

To the glass insert was added 1.0 g dibenzothiophene (DBT), 3.87 g tetrabutylammonium hexafluorophosphate (TBAPF$_6$), and 100 milliliters ("ml") anhydrous dimethyl sulfoxide (DMSO, Aldrich). After the content was dissolved, the glass insert was loaded into the autoclave body, the autoclave head assembled and pressure tested. The autoclave was charged with 70 psig of N_2 and heated to 212° F. (100° C.) with stirring (300 rpm). A voltage of 5 Volts was applied and the current was 0.8 Amp. The current gradually decreased with time and after two hours, the run was stopped. The autoclave was opened and the content acidified with 10% HCl

(50 ml). The acidified solution was then diluted with 100 ml of de-ionized ("DI") water, extracted with ether (50 ml×3). The ether layer was separated and dried over anhydrous Na_2SO_4, and ether was allowed to evaporate under a stream of N_2. The isolated dry products were analyzed by GC-MS. A conversion of 12% was found for DBT and the products are as the following.

[2]



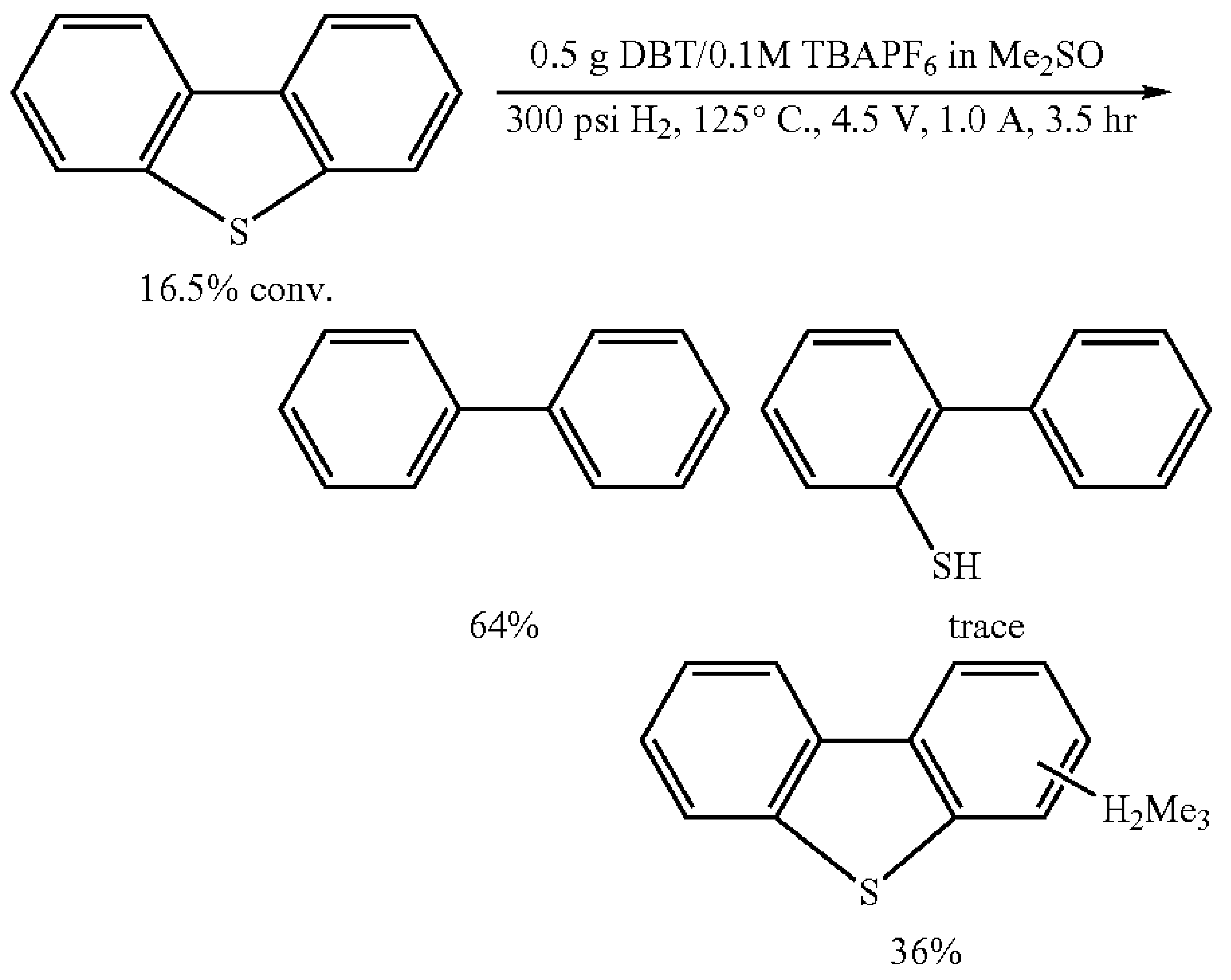
This example shows that the electrochemical reduction of DBT under N_2 resulted in: 12% DBT conversion after 2 h at 212° F. GC-MS revealed that the products consisted of 35% 2-phenyl benzenethiol, 8% tetrahydro-DBT, and 57% of a species with a mass of 214. The assignment of this peak as 2-phenyl benzenethiol was done by comparing with an authentic sample. The mass 214 species was tentatively assigned as 2-phenyl benzenethiol with two methyl groups added. Addition of methyl groups to DBT indicates that decomposition of solvent DMSO occurred since it is the only source of methyl groups in this system. No desulfurization product biphenyl was observed in this run.

Example 1

Electrochemical Treatment of DBT Under H_2 in Dimethyl Sulfoxide Solvent with Tetrabutylammonium Hexafluorophosphate Electrolyte

To the glass insert was added 0.5 g DBT, 3.87 g tetrabutylammonium hexafluorophosphate ($TBAPF_6$), and 100 ml anhydrous dimethyl sulfoxide (DMSO, Aldrich). After the content was dissolved, the glass insert was loaded into the autoclave body, the autoclave head assembled and pressure tested. The autoclave was charged with 300 psig of H_2 and heated to 257° F. (125° C.) with stirring (300 rpm). A voltage of 4.5 Volts was applied and the current was 1.0 Amp. The current gradually decreased with time and after three and half (3.5) hours, the run was stopped. The autoclave was opened and the content acidified with 10% HCl (50 ml). The acidified solution was then diluted with 100 ml of DI water, extracted with ether (50 ml×3). The ether layer was separated and dried over anhydrous Na_2SO_4, and ether was allowed to evaporate under a stream of N_2. The isolated dry products were analyzed by GC-MS. A conversion of 16.5% was found for DBT and the products are as the following.

[3]

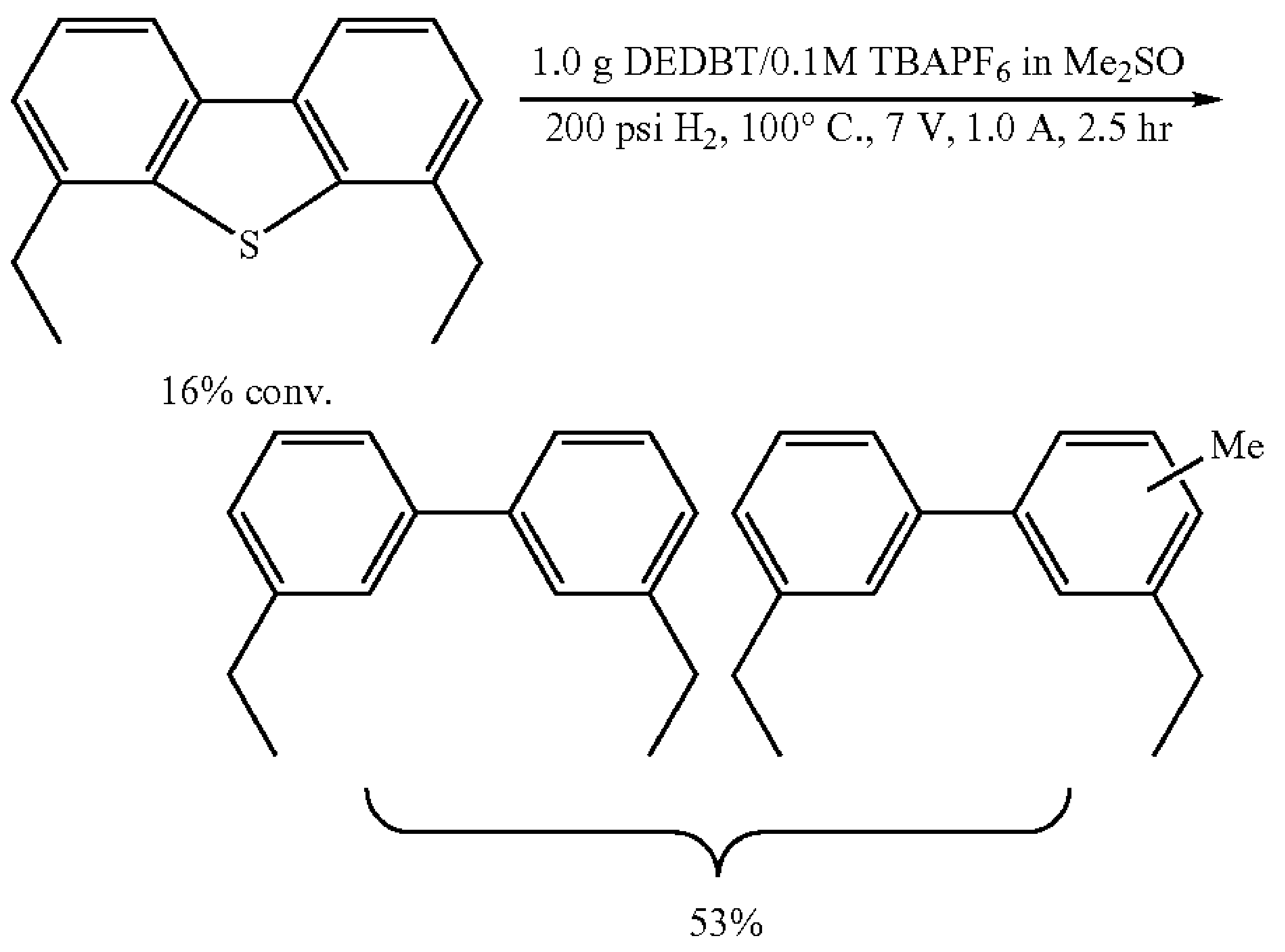


Example 2

Electrochemical Treatment of DEDBT Under H_2 in Dimethyl Sulfoxide Solvent with Tetrabutylammonium Hexafluorophosphate Electrolyte

To the glass insert was added 1.0 g 4,6-diethyl dibenzothiophene (DEDBT), 3.87 g tetrabutylammonium hexafluorophosphate ($TBAPF_6$), and 100-ml anhydrous dimethyl sulfoxide (DMSO, Aldrich). After the content was dissolved, the glass insert was loaded into the autoclave body, the autoclave head assembled and pressure tested. The autoclave was charged with 200 psig of H_2 and heated to 212° F. (100° C.) with stirring at about 300 rpm. A voltage of 7 Volts was applied and the current was 1.0 Amp. The current gradually decreased with time and after two and half (2.5) hours, the run was stopped. The autoclave was opened and the content acidified with 10% HCl (50 ml). The acidified solution was then diluted with 100 ml of DI water, extracted with ether (50 ml×3). The ether layer was separated and dried over anhydrous Na_2SO_4, and ether was allowed to evaporate under a stream of N_2. The isolated dry products were analyzed by GC-MS. A conversion of 16% was found for DEDBT and the products are as the following.

[4]



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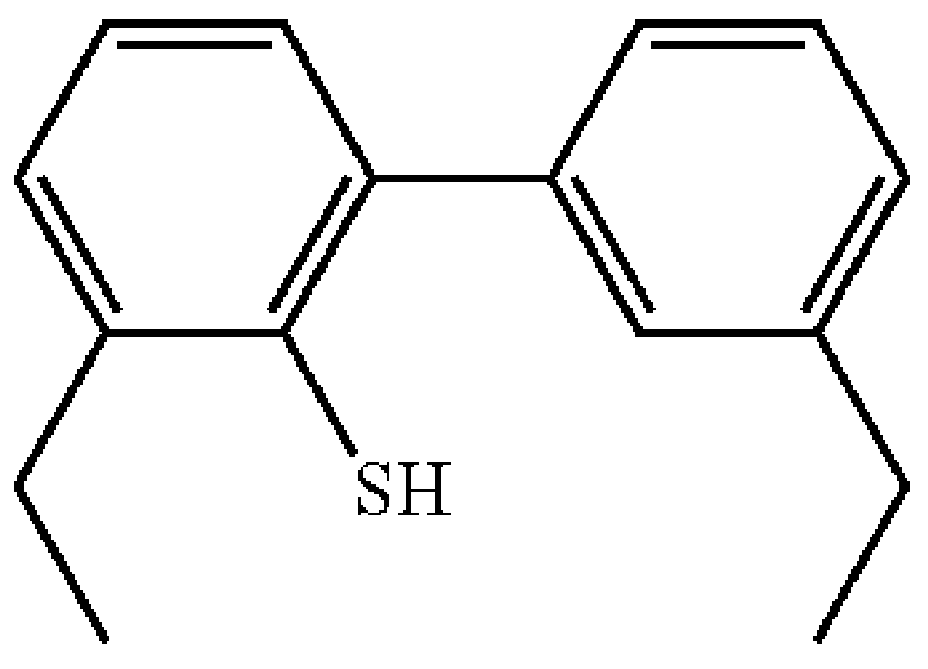
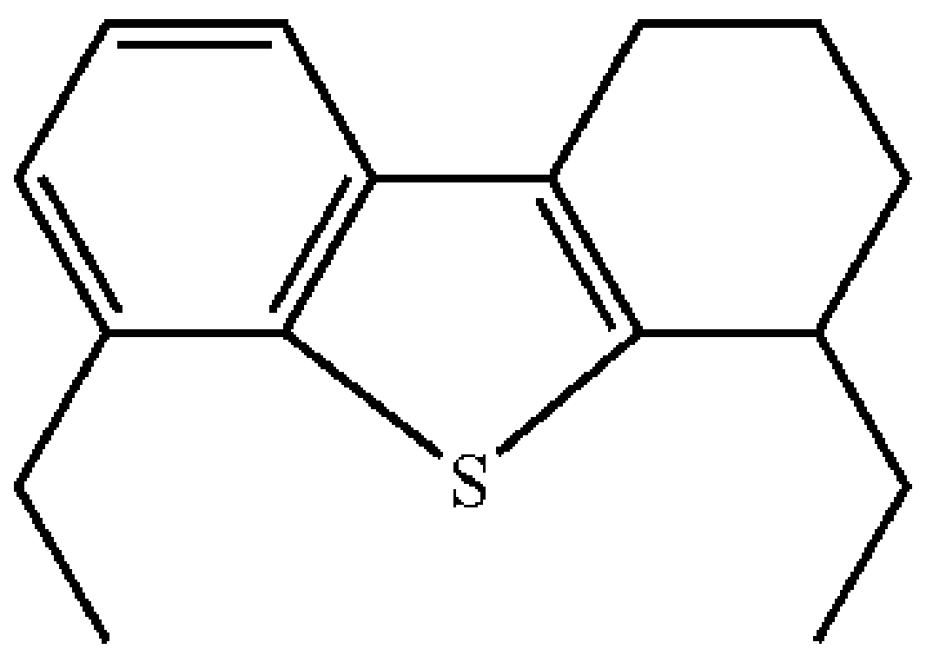


46%



trace

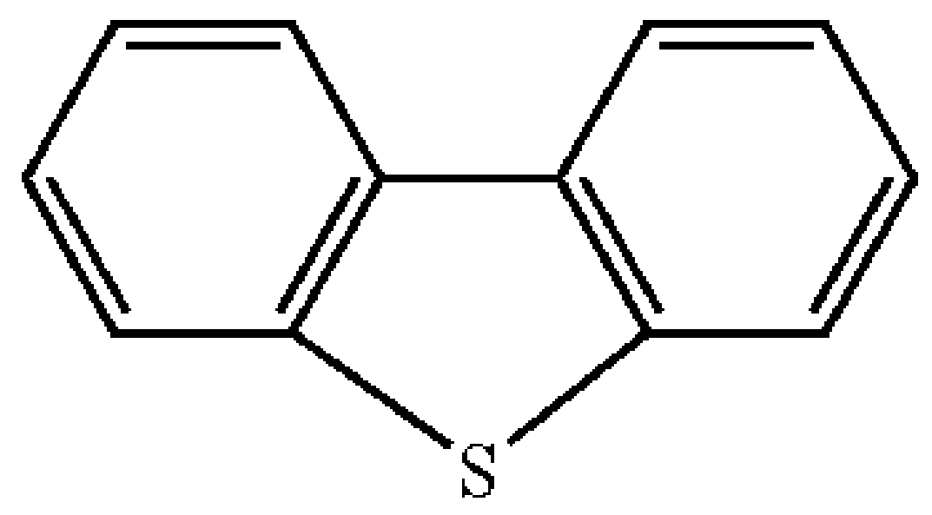
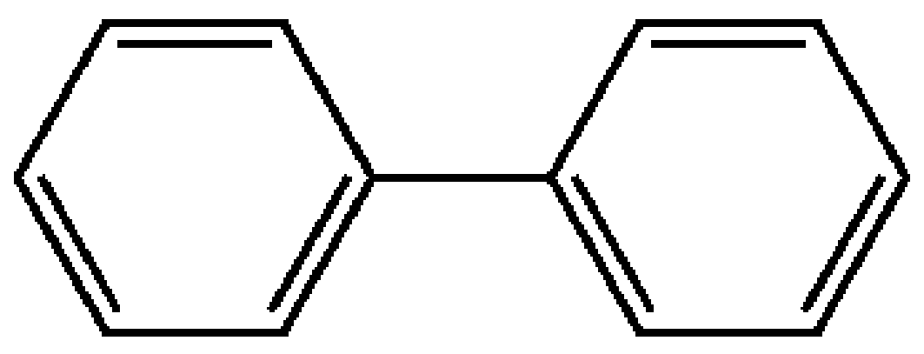
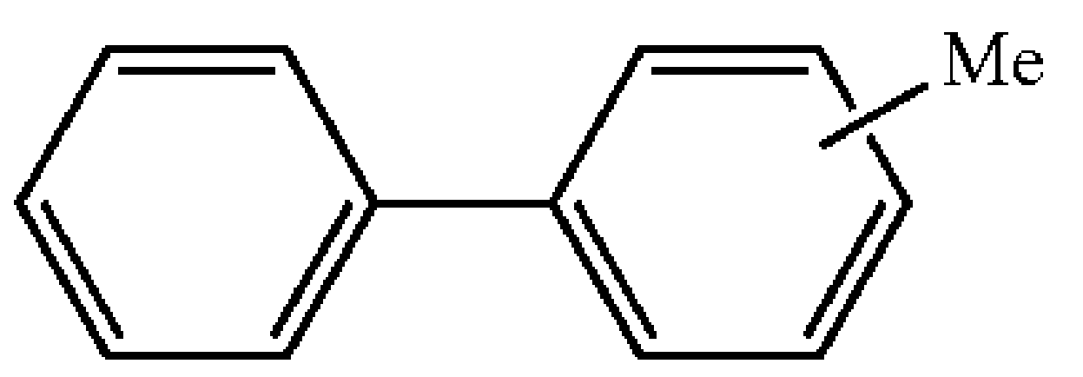
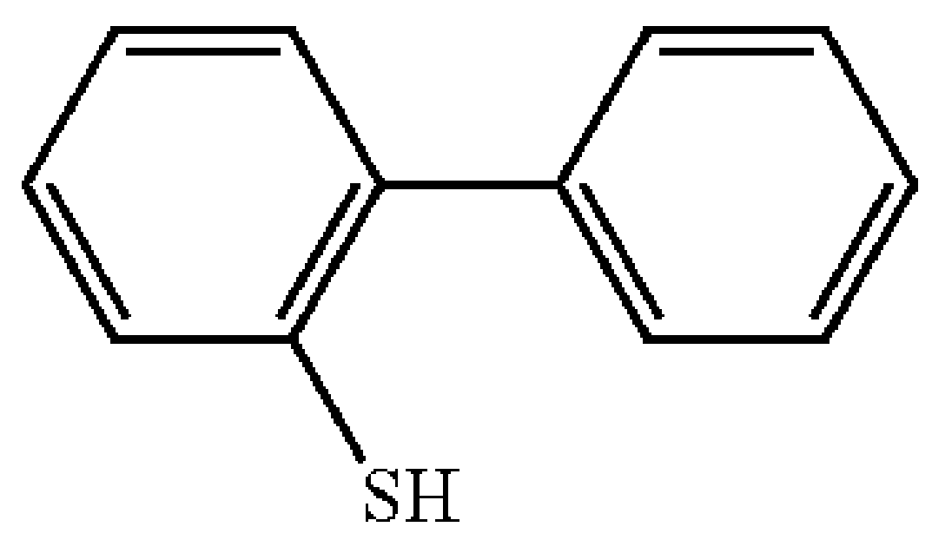
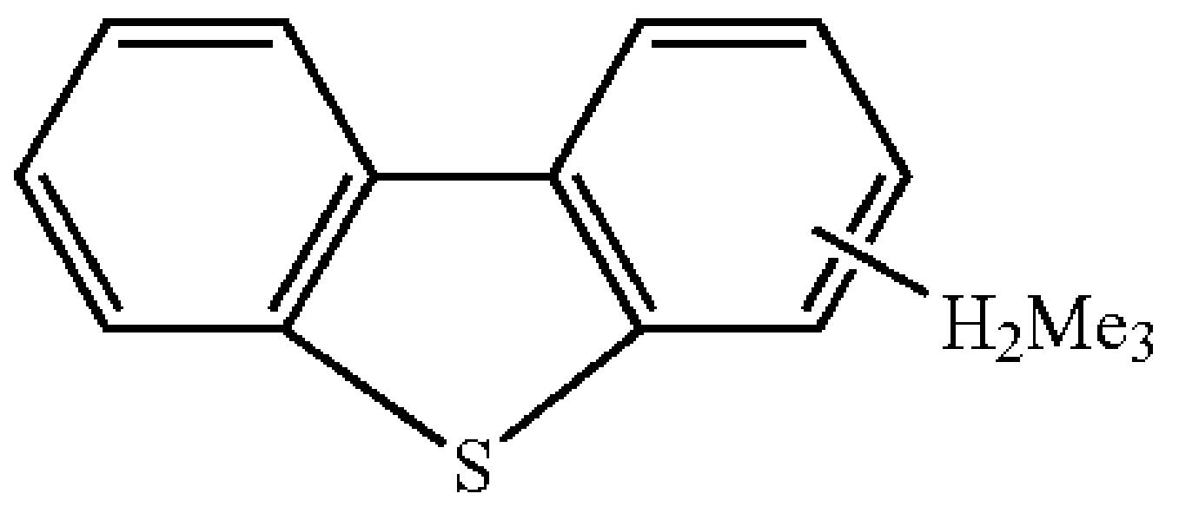
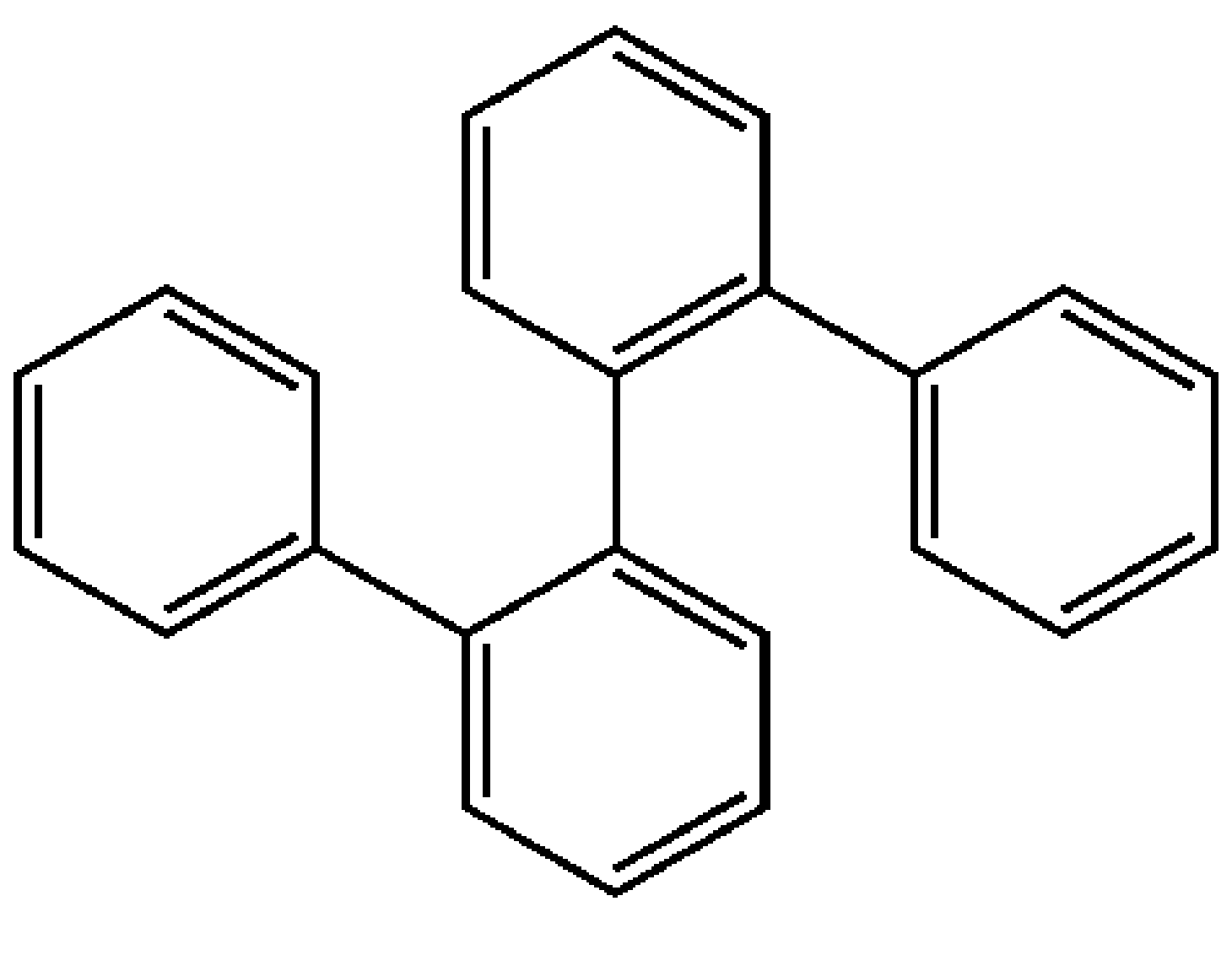
Similarly, desulfurization was also observed for sterically hindered Diethyl Dibenzothiophene (DEDBT) under H_2. The conversion was ca. 16% and the products contained 53% desulfurized compounds, 46% dihydro-DEDBT and a trace amount of tetrahydro-DEDBT. Solvent decomposition also occurs in this case. Although electrochemical desulfurization of DBT and hindered DBT has been achieved under H_2 in the 77° F. to 257° F. (25° C. to 125° C.) temperature range, the conversion is still quite low.

Example 3

Room Temperature Electrochemical Reduction of Dibenzothiophene (DBT) in DMSO under Hydrogen

As a proof of concept, it is critical to demonstrate that high conversion and high degree of desulfurization can be achieved. In this example, it was discovered that, at room temperature, the DMSO/Bu_4NPF_6 system allows the electrochemical reduction of DBT to be run for an extended period of time. Thermal degradation of the solvent/electrolyte is minimal at room temperature. Conversion of DBT and product distribution is listed in Table 1. Each row in the table represents a separate experiment run under identical conditions except for the length of electrolysis (0.5 g DBT, 4.0 g Bu_4NPF_6, 100 ml DMSO, 300 psig H_2, 4.5 V cell voltage, 77° F. (25° C.), acidic work-up). The electrolysis is clean under these conditions; and the products were isolated following the acidic work-up procedures and analyzed by GC-MS. The assignment for DBT-H_2Me_3 is tentative; assignments for other products are of high confidence, either by comparing with authentic samples or by good-quality match to the standard in the mass spectrum library. At short run time (3 h and 17 h), the products are 100% desulfurized. As the conversion goes up with increasing run time, small amounts of 2-phenyl benzenethiol and methylated DBT were observed. A small amount of heavy product, tetraphenyl, was also found at long run length (72 h and 163.5 h), which was probably formed from secondary electrochemical reactions. A conversion of 94% was achieved in a week, with the desulfurized products accounting for ~98% of the products. The overall degree of desulfurization is >90%. The conversion appears to follow first-order kinetics, with a simulated rate constant of 3.5×10^{-6} s^{-1} at room temperature (FIG. 2). These examples demonstrate that a high degree of desulfurization is achievable at room temperature, thus validating the concept of electrochemical desulfurization under hydrogen gas.

TABLE 1

Time (h)	 Conv. (%)	 (%)	 (%)	 (%)	 (%)	 (%)
3	2	100				
19	12	83	17			
72	56	85	7	2	3	3
163.5	94	81	13	0.8	1.4	3.4

What is claimed is:

1. A process for removing sulfur from heavy oil feedstreams containing sulfur-containing molecules, which process comprises:

a) heating and pressurizing said heavy oil feedstream to a temperature of about 400° F. (204° C.) to about 800° F. (426° C.) and a pressure of about 200 psig to about 700 psig;

b) passing said heated and pressurized heavy oil feedstream and an effective amount of hydrogen to an electrochemical cell and subjecting the heavy oil feedstream to a voltage in the range of about 4V to about 500V and a current density of about 10 mA/cm^2 to about 1000 mA/cm^2, thereby reducing at least a portion of the sulfur-containing molecules to hydrogen sulfide and resulting in a product stream comprised sulfur-lean heavy oil product stream and hydrogen sulfide;

c) separating said hydrogen sulfide from said sulfur-lean heavy oil product stream in a gas/liquid separation zone; and

d) recovering the sulfur-lean heavy oil product stream.

2. The process of claim **1**, wherein at least about a 10 wt. % fraction of said heavy oil feedstream boils at a temperature of at least about 1050° F. (565° C.).

3. The process of claim **2**, wherein at least about a 25 wt. % fraction of said heavy oil feedstream boils at a temperature of at least about 1050° F. (565° C.).

4. The process of claim **2**, wherein the heavy oil feedstream is comprised of a bitumen.

5. The process of claim **1**, wherein the heavy oil feedstream is heated to a temperature of about 350° F. (176° C.) to about 500° F. (260° C.) and pressurized to a pressure of about 300 psig to about 500 psig.

6. The process of claim **1**, wherein the electrochemical cell is a divided electrochemical cell.

7. The process of claim **1**, wherein the electrochemical cell is operated at a voltage of about 100 volts to about 200 volts.

8. The process of claim **3**, wherein the electrochemical cell is operated at a voltage of about 100 volts to about 200 volts.

9. The process of claim **8**, wherein the heavy oil feedstream is heated to a temperature of about 350° F. (176° C.) to about 500° F. (260° C.) and pressurized to a pressure of about 300 psig to about 500 psig.

10. The process of claim **9**, wherein the heavy oil feedstream is comprised of a bitumen.

11. The process of claim **1**, wherein there is a gap between the cathode and the anode of the electrochemical cell of about 1 to about 25 mm.

12. The process of claim **1**, wherein the linear velocity of the heavy oil feedstream within the electrochemical cell is from about 1 to about 500 cm/s.

13. The process of claim **10**, wherein there is a gap between the cathode and the anode of the electrochemical cell of about 1 to about 25 mm and the linear velocity of the feedstream within the electrochemical cell is from about 1 to about 500 cm/s.

14. The process of claim **1**, wherein the hydrogen sulfide is sent to a process unit wherein at least a portion of the sulfur is separated from the hydrogen.

15. The process of claim **10**, wherein the hydrogen sulfide is sent to a process unit wherein at least a portion of the sulfur is separated from the hydrogen.

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